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Charmed Mesons Fragmentation Functions

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Abstract

Fragmentation functions for heavy-light mesons, like the charmed D , D^* mesons, are proposed. They rest on next-to-leading QCD Perturbative Fragmentation Functions for heavy quarks, with the addition of a non-perturbative term describing phenomenologically the quark \rightarrow meson transition. The cross section for production of large p_T D , D^* mesons at the Tevatron is evaluated in this framework.

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1 Introduction

Much experimental and theoretical work has been recently devoted to the study of heavy flavour production in hadronic collisions. Theoretically, because the heavy quark mass is setting the scale in the perturbative expansion of QCD, acting as a cut-off for the infrared singularities, the most relevant features of this process are calculable within perturbation theory. Indeed the calculation in perturbative QCD of the differential and total cross sections to order α_s^3 has been performed [1], thus providing a firm basis for a detailed study of the properties of the bottom and charm quarks.

The NLO one particle inclusive differential distribution will however contain terms of the kind $\alpha_s \ln(p_T/m)$ which, in the large p_T limit, will become large and will spoil the perturbative expansion of the cross section. This is reflected in a large sensitivity to the choice of the renormalization/factorization scales and hence in a large uncertainty in the theoretical prediction. In Ref. [2] this problem was tackled by introducing the technique of the Perturbative Fragmentation Functions (PFF) through which these terms were resummed to all orders and the cross section was shown to display a milder scale sensitivity.

When considering heavy meson inclusive production, non perturbative effects are also quite important, especially for charmed mesons (being $m_c \approx 1.5$ GeV), so they have to be estimated as better as possible for a reliable calculation of the production cross sections. They are normally introduced within the formalism of FF and indeed a next-to-leading order(NLO) analysis of FF into charmed mesons (in particular D, D^*) including non-perturbative effects has been performed in Ref. [3] for e^+e^- annihilation processes up to LEP energies. In this analysis however the charm component in the FF is considered only, the other components giving a small contribution to the e^+e^- production cross section.

On the other hand, the contribution of gluon-gluon and quark-gluon scattering subprocesses to the production cross section is relevant in hadronic collisions, and the gluonic component can no longer be neglected.

Thus we proceed in this paper to the construction of a set of NLO fragmentation functions for D, D^* mesons, including gluon, light and anticharm quark contribution. This set can therefore be used in the calculation of large p_T inclusive production cross section for any hard collision process.

2 Theoretical framework

The general framework of this analysis is the following: we'll consider the fragmentation into charm quark of any parton produced at large transverse momen-

tum $p_T \gg m_c$, followed by the hadronization of the charm quark into the meson. Exploiting the difference in time scales of the two processes, short for the perturbative fragmentation of the parton into the charm and longer for the non-perturbative hadronization of the charm in a meson, we can factor the overall fragmentation function of the parton i into the meson H in the following way:

$$D_i^H(z, \mu, m_c) = D_i^c(z, \mu, m_c) \otimes D_{np}^H(z) \quad (1)$$

the \otimes symbol meaning the usual convolution operation. This expression represents our ansatz for the fragmentation of a parton into a charmed meson. The non perturbative part of the fragmentation is taken to be universal, i.e. independent of the parton which produced the charm quark via perturbative cascade. It is also independent of the scale at which the fragmentation function is taken: all the evolution effects are dumped into the perturbative part.

The first part of the process can be calculated with purely perturbative techniques at an initial scale of the order of the charm mass, while we have to rely on phenomenological inputs to extract the hadronization non-perturbative effects at a fixed scale. Then using the DGLAP evolution equations at NLO accuracy we can evaluate fragmentation functions at the appropriate scale $\mathcal{O}(p_T)$, assuming that no scaling violation effects arise in the non perturbative part of the fragmentation function.

The calculation of the perturbative part of the process has been carried out in Ref. [4]. For the reader's convenience we shall briefly report the main results of this analysis. Using the factorization property, the charm quark production cross section in e^+e^- collisions can be written as:

$$\frac{d\sigma}{dx}(x, Q, m_c) = \sum_i \int_x^1 \frac{d\hat{\sigma}_i}{dx}\left(\frac{x}{z}, Q, \mu\right) D_i^c(z, \mu, m_c) \frac{dz}{z} \quad (2)$$

where x is the energy fraction of the charm quark, Q is the center-of-mass energy and m_c is the charm mass. Eq.(1) shows that the cross section is factorized into a short-distance term $\frac{d\hat{\sigma}_i}{dx}$ for the production of the massless parton i , and a parton FF D_i^c into the charm quark, evaluated at a scale μ . When μ is taken to be of the order of m_c , $D_i^c(x, \mu, m_c)$ is expressed in a perturbative expansion in powers of α_s :

$$D_i(z, \mu, m_c) = d_i^{(0)}(z) + \frac{\alpha_s}{2\pi} d_i^{(1)}(z, \mu, m_c) + \mathcal{O}(\alpha_s^2) \quad (3)$$

Then using the perturbative expansion of the l.h.s. of eq.(2) one obtains the explicit expression of $d_i^{(0)}$ and $d_i^{(1)}$ coefficients.

This has been explicitly done in Ref. [4], obtaining the following set of NLO initial conditions in \overline{MS} scheme for the fragmentation function of a charm quark, gluon and

light quarks respectively, into the charm quark:

$$\hat{D}_c^c(x, \mu_0) = \delta(1-x) + \frac{\alpha_s(\mu_0)C_F}{2\pi} \left[\frac{1+x^2}{1-x} \left(\log \frac{\mu_0^2}{m_c^2} - 2 \log(1-x) - 1 \right) \right]_+ \quad (4)$$

$$\hat{D}_g^c(x, \mu_0) = \frac{\alpha_s(\mu_0)T_f}{2\pi} (x^2 + (1-x)^2) \log \frac{\mu_0^2}{m_c^2} \quad (5)$$

$$\hat{D}_{q,\bar{q},\bar{c}}^c(x, \mu_0) = 0 \quad (6)$$

where μ_0 is taken of the order of the charm quark mass, which we fix in our analysis at 1.5 GeV. As obvious, D_g^c is of order α_s , and $D_{q,\bar{q},\bar{c}}^c$ is zero in the NLO approximation, being of the order of α_s^2 . Nonetheless, this component is generated at higher scales through the evolution with DGLAP equations, which involve a mixing of all parton components of FF.

The PFF initial conditions (4,5,6), evolved up to the appropriate scale $\mathcal{O}(p_T)$ with NLO accuracy, can be used to evaluate the open charm production cross section in the large p_T region. Indeed this allows the resummation of potentially large logarithms of the kind $\alpha_s \log(p_T/m_c)$, arising from quasi-collinear configurations, thus recovering a more reliable prediction of the p_T spectrum at large transverse momentum than the fixed order $\mathcal{O}(\alpha_s)$ calculation. This is discussed in detail in Ref. [2] in the case of b quarks and in ref. [5] for charm photoproduction.

In order to obtain the inclusive production of D, D^* mesons, one has to take into account further the hadronization of the charm quark into the final charmed meson. The Perturbative Fragmentation Functions (4,5,6) can be convoluted with a non-perturbative part, which we parametrize as

$$D_{np}^H(z) = \langle n_H \rangle A(1-z)^\alpha z^\beta \quad (7)$$

$$\frac{1}{A} = \int_0^1 (1-z)^\alpha z^\beta dz$$

where the parameters α , β and $\langle n_H \rangle$ have to be extracted from comparison with experimental data at a fixed scale. Indeed α and β have been obtained by Colangelo and Nason in Ref. [3] by fitting ARGUS data [6] for D, D^* mesons fragmentation functions in e^+e^- collisions at center-of-mass energy of 10.6 GeV. They are reported in Table 1. We'll use their determination, on the ground of our universality assumption for the non-perturbative part of the fragmentation functions. It is worth mentioning that we have challenged this universality assumption by comparing our fragmentation functions (1), evolved up to 90 GeV and using the ARGUS parameters of Table 1, with LEP data by OPAL [7]. Reasonable agreement has been found, giving support to our hypothesis. It is also worth noting that Colangelo and Nason original work [3] gives a sub-set of our fragmentation functions only, since they were addressing

Meson	α	β	$\langle n_H \rangle$	$\langle n_H \rangle$
D^0	1.0	3.67	0.58	0.58
D^{*0}	0.6	5.4	0.3	0.29
	Colangelo/Nason		HERWIG	JETSET

Table 1: Collection of parameters which describe the non-perturbative part of the fragmentation functions. In the Colangelo-Nason paper, ref. [3], these α and β were obtained with $\Lambda_5 = 100$ MeV.

the non-singlet component, by far the dominant one in the large z region. We deal instead with the whole set, including mixings with gluons and antiquarks: a more complete analysis of D mesons production in e^+e^- collisions at LEP with the full set, extending also down to small- z values, will be presented elsewhere [8].

The parameter $\langle n_H \rangle$ in eq. (7) is the mean multiplicity of charmed mesons produced in the process, i.e. how many mesons does the non-perturbative fragmentation of a c quark produce. In the analysis of Ref. [3] the normalization condition fixed by $\langle n_H \rangle$ has not been determined. We have therefore used the mean multiplicity simulated by the HERWIG generator in the process $e^+e^- \rightarrow c\bar{c}$ at 90 GeV. This provides us with the last missing parameter for fully defining the non perturbative part of the fragmentation function. The values we used are summarized in Table 1: they describe either the non perturbative fragmentation of a charm into a D^0 or a D^{*0} , or alternatively of an anticharm into a \bar{D}^0 or a \bar{D}^{*0} . As a double check, the same multiplicities have also been extracted from JETSET, by fragmenting a charm quark of 5.3 GeV energy. They are also reported in Table 1, and can be seen to agree well. It must be noted that the D mesons multiplicities include the feed-down from the D^* decays. It is also worth noticing that the non-perturbative fragmentation function (7), with the parameters shown in Table 1, compares nicely with a Peterson fragmentation function with $\epsilon = 0.06$, used for instance in [12] to describe the transition from c quarks to D mesons.

The use of an explicit parametrization for the FF at a given scale extracted from HERWIG has been successfully made in the past for the case of the inclusive production of light and strange mesons [13]. In these papers not only the multiplicity but also parameters α and β dictating the shape of the FF (see Table 2) were extracted from HERWIG at some large scale. We have refrained from doing so in this work, since the large mass of the charm quark provides us with a solid ground for evaluating in pQCD at least the perturbative part of the fragmentation function, see eq. (1). For the sake of completeness we do however provide in Fig. 1 a comparison between the fragmentation function which we obtain by evolving the ansatz of eq. (1) and that we get using the HERWIG parametrization given in Table 2, at a scale of 90 GeV.

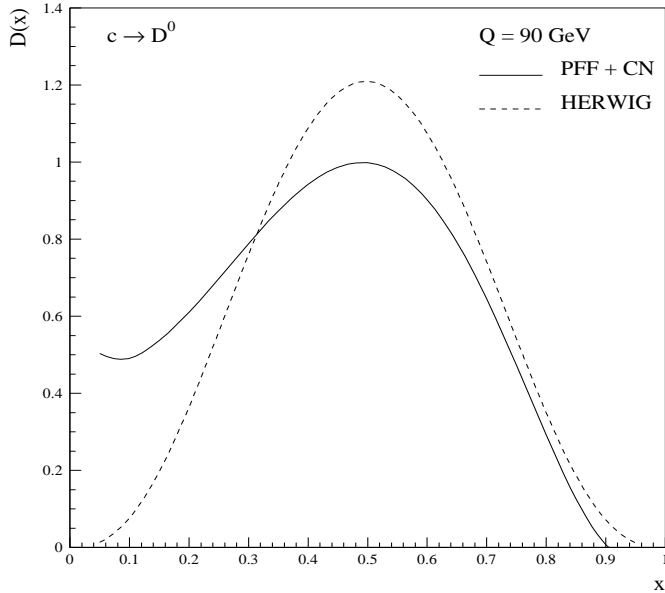


Figure 1: Comparison between the $D_c^{D^0}$ fragmentation function produced by HERWIG at 90 GeV and the one given by our ansatz (1) with the non-perturbative parameters by Colangelo and Nason (see table 1).

The value of $\Lambda_5 = 100$ MeV has been used in the evolution, for consistency with the Colangelo-Nason fits [3]. The Sudakov form factor [4] has also been included, as it was taken into account in ref. [3]. Its effects are however small, of the order of a few percent, both on the fragmentation function itself and on the cross sections which will follow.

A number of comments about this plot are in order. The discrepancy in the small x region is due to the PFF being enhanced by mixing with the gluon splitting kernel, while the HERWIG result is suppressed by phase space constraints. This difference is however of no practical importance in the evaluation of hadronic cross sections, since such small x values probe the very large p_T tail of the kernel cross section, where the latter is small. The discrepancy around the maximum can instead be considered as a normalization off-set, which could be eliminated by a fine tuning of both FFs to some experimental data. It is however worth noticing that the present accuracy of the data is not better than the uncertainty originating from the difference of the two FFs. Moreover, the consequences on the observable hadronic cross section are small.

	α	β	N_H^i	$\langle n_H^i \rangle$
$c \rightarrow D^0$	2.75 ± 0.08	2.72 ± 0.03	53.6	0.58
$g \rightarrow D^0$	1.12 ± 0.51	0.36 ± 0.19	0.0045	0.0013
$c \rightarrow D^{*0}$	2.01 ± 0.06	2.42 ± 0.08	12.4	0.30
$g \rightarrow D^{*0}$	0.16 ± 0.08	0.016 ± 0.03	0.008	0.007

Table 2: Collection of parameters which describe the fragmentation functions produced by HERWIG at 90 GeV, parametrized as $D_i^H(z) = N_H^i(1-z)^{\alpha_i}z^{\beta_i}$. It also holds $\langle n \rangle = NB(\alpha+1, \beta+1)$, B being the Euler Beta function representing the normalization integral of the FF. Note that the parameters α and β do not have to coincide with those of eq. (7), because they include also the perturbative component of the FF.

3 Results

Using the perturbative initial conditions (4,5,6) and the non-perturbative parametrization (7) with the parameters summarized in Table 1, we have a NLO evaluation of the parton FF in D, D^* mesons at a scale $\mu_0 \approx m_c$. Then using the DGLAP evolution equations to NLO accuracy one can evaluate the fragmentation functions set at any desired factorization scale μ . By convoluting this set with the NLO kernel cross sections for massless parton scattering [11] one gets a prediction for D and D^* production at large p_T at a hadron collider. Figures 2a,b show the p_T and rapidity spectra for the Tevatron. Also shown (solid line) is the pure charm quark NLO cross section, as predicted by the Perturbative Fragmentation Function approach. These results have been obtained with the MRS-A structure functions set [14] and with a Λ_5 value of 100 MeV. The Sudakov form factor [4] has also been included: we notice here once more that its effects are numerically small, below 10%, in the p_T -rapidity range we have considered.

As expected the D mesons cross sections lie below the charm quark one. It can however be checked that summing them up and introducing an additional factor of two to allow for D^+ and D^{*+} state (which are assumed to fragment like the neutral ones) the charm cross section is almost reproduced (wide-dotted line). The small residual gap is given by the mesons FF being softer and therefore producing a smaller cross section.

Many uncertainties do of course affect this result, though not shown in the plots. First of all, the mesons fragmentation functions will share all the uncertainties related to the heavy quark PFFs on which they are built on. Factorization scale and initial scale dependencies, of the kind studied in [2], will also appear here with a similar behaviour, leading to an uncertainty of order 20-30%. These fragmentation functions will also share the same shortcomings of the PFFs. This means that their description

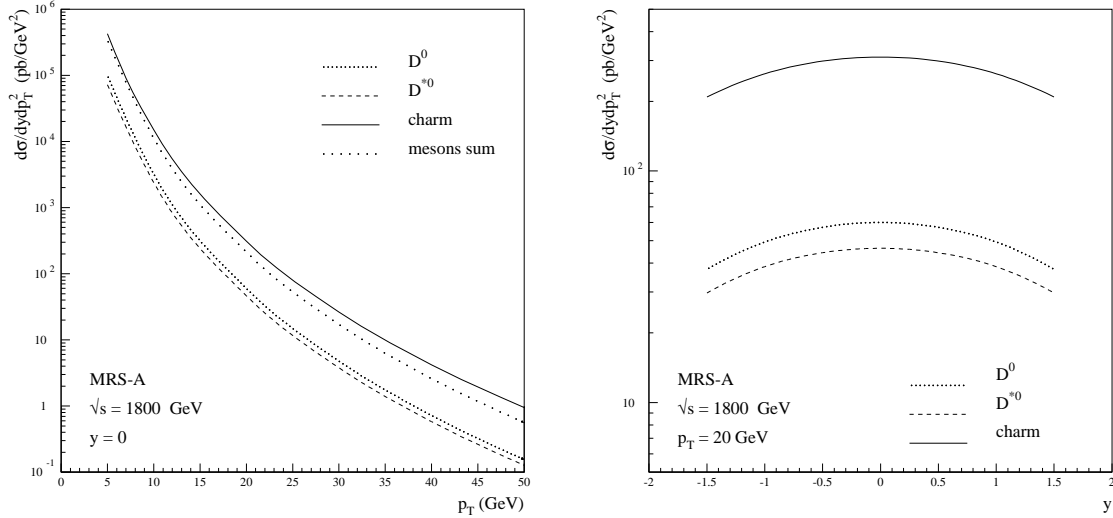


Figure 2: Cross sections for mesons production at the Tevatron, as predicted by our fragmentation functions approach. Comparison with the pure charm quark cross section is also shown. The mesons sum also includes D^+ and D^{*+} contributions.

is not accurate at low p_T and at the edges of phase space (see also [5] for a discussion of this point), where unresummed higher order corrections and non-perturbative effects play an important role. This leads to the impossibility of performing a meaningful comparison with the D^* photoproduction data collected at HERA, since the minimum p_T , of the order of 2-3 GeV, is too low and the edges of phase space in rapidity are probed.

A second kind of uncertainty is related to the determination of the non-perturbative parameters α , β and $\langle n_H \rangle$. The set we have chosen was fitted to ARGUS data, and has been picked mainly for illustrative purposes, although, as stated above, it reproduces fairly well the actual OPAL data from LEP. An analysis of all LEP data, when available, will certainly lead to a more precise determination of these parameters. Of course also a detailed measurement of the D , D^* inclusive cross sections at the Tevatron would be very helpful and give complementary information on the FF, particularly for the gluon terms.

To conclude, we have presented a model for the D and D^* fragmentation functions based on PFF for heavy quarks complemented by a factorized non-perturbative term describing the quark-meson transition. Predictions have been given for large p_T charmed mesons production at the Tevatron.

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